# The shock-patterned solar chromosphere in the light of ALMA


*Sven Wedemeyer-Böhm (Kiepenheuer-Institut für Sonnenphysik, Freiburg )*
*Hans-Günter Ludwig (Lund Observatory, Lund, Sweden)*
*Matthias Steffen (Astrophysikalisches Institut Potsdam, Potsdam)*
*Bernd Freytag (GRAAL, Université de Montpellier II, Montpellier, France)*
*Hartmut Holweger (Inst.f.Theo.Phys.u.Astrophys., Universität Kiel)*
http://www.kis.uni-freiburg.de/~sven sven@kis.uni-freiburg.de


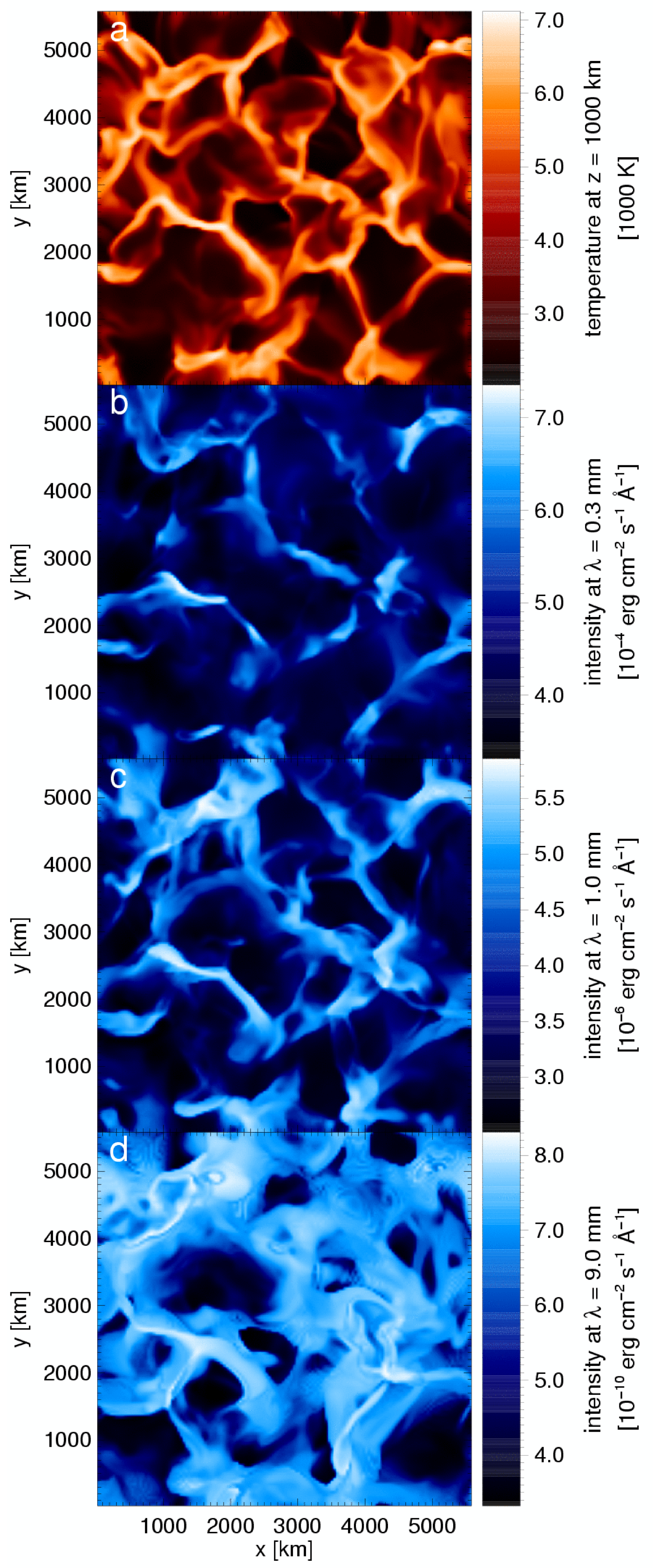


**Fig.1: a:** horizontal 2D temperature slice at a height of z=1000km. **b-d:** emergent continuum intensity at $\lambda$= 0.3 mm, 1.0 mm, and 9.0 mm, resp..

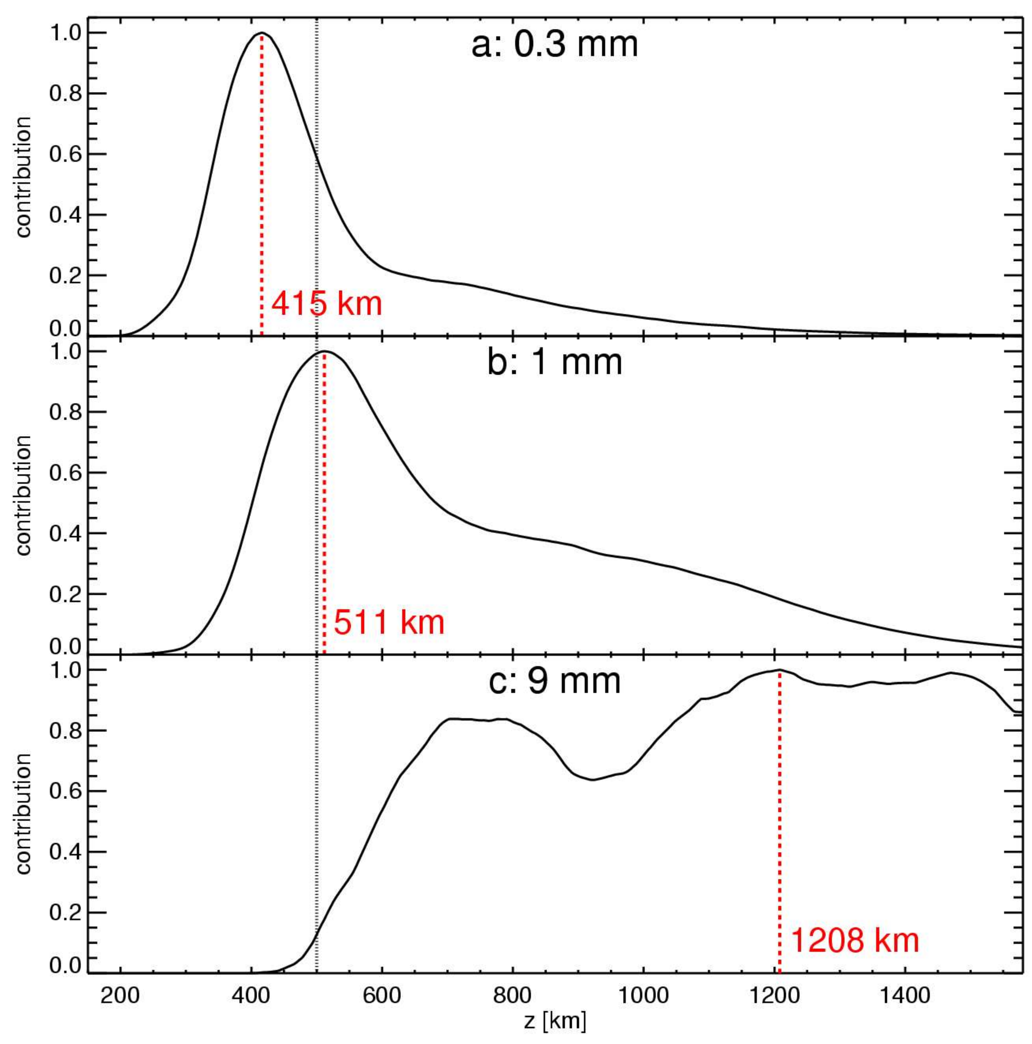


**Fig.2:** intensity contribution functions for $\lambda$= 0.3 mm, 1.0 mm, and 9.0 mm, resp.. The dotted lines separate photosphere and chromosphere at z=500km. The red dashed lines mark the height of the maximum contribution.

## Introduction

Recent three-dimensional non-magnetic radiation hydrodynamics simulations by Wedemeyer et al. (2004) suggest that the solar chromosphere is highly structured in space and time on scales of only 1000 km and 20-30s, resp.. The resulting pattern consists of a network of hot gas (shock waves) and enclosed cool regions which are due to the propagation and interaction of shock fronts (**Fig.1a**).

In contrast to many other diagnostics, the radio continuum at millimetre wavelengths is formed in LTE, and provides a rather direct measure of the thermal structure. It thus facilitates the comparison between numerical model and observation.

While the involved time and length scales are not accessible with todays equipment for that wavelength range, the next generation of instruments, such as the **Atacama Large Millimetre Array (ALMA)**, will provide the required resolution.

## Atacama Large Millimetre Array

According to Bastian (2002), ALMA will provide an angular resolution of 0."015 to 1."4, depending on antenna configuration, corresponding to ~10km to ~1000km on the Sun. There will be ten frequency bands which cover a total range from 31.3GHz ($\lambda$=9.58mm) to 950GHz ($\lambda$=0.32mm). The primary beam size of an ALMA antenna will be 21" at $\lambda$=1mm which is thus sufficient to observe the interior of an internetwork region.

A major advantage of ALMA for solar research lies in the properties of its wavelength range. The (sub-)millimetre radiation originates from the low and middle chromosphere and is thus mainly due to two sources of opacity, namely thermal free-free opacity and $H^-$ opacity. Hence, the assumption of local thermodynamic equilibrium (LTE) is valid and, moreover, the source function is Planckian. Consequently, the gas temperature in the contributing height range translates linearly into intensity at these wavelengths, allowing **ALMA to directly map gas temperature of the low and middle chromosphere.**

## The hydrodynamic model

Here we use the numerical 3-D model by Wedemeyer et al. (2004), calculated with the radiation hydrodynamics code **CO⁵BOLD** (Freytag, Steffen & Dorch, 2002). Magnetic fields are not included, restricting the model to internetwork regions. The resolution of the model atmosphere is 40km in horizontal (x,y) and 12km in vertical direction (z). The top of the model is located at a height of z=1710km in the middle chromosphere, while the horizontal extension is 5600 km (~7".7).

## Radiative transfer calculations

The continuum images were computed with the 3D LTE spectrum synthesis code **LINFOR3D**, which was developed by Steffen & Ludwig (based on the Kiel code LINFOR/LINLTE).

For convenience we adopt the following wavelengths for the spectrum synthesis: 0.3mm (~1000 GHz), 1mm (~300 GHz), and 9mm (~33 Ghz), covering the accessible range. A time sequence of intensity images has been calculated for each wavelength.

## Results

The horizontal temperature cross-section in **Fig.1a** shows a pattern which is characteristic for the model chromosphere, consisting of thin filaments of hot gas (shock waves) and embedded cool regions. The intensity maps in **Fig.1b-d** look more or less similar but sample different height ranges as can be seen in **Fig.2**. At $\lambda$=0.3mm the maximum intensity contribution originates from the upper photosphere (z=415km), whereas the chromosphere contributes only little compared to the intensity at $\lambda$=1mm. At that wavelength the chromosphere produces a significant fraction, while the maximum is still located at the chromospheric base (z=511km). At $\lambda$=9mm, however, the intensity is due to a large height range throughout the whole model chromosphere, even exceeding its vertical extent.

The distributions of the data displayed in **Fig.1** are plotted as histograms in **Fig.3**. The double-peaked character of the chromospheric gas temperature distribution (due to the co-existence of hot shocked gas and cool regions) is most closely reproduced by the intensity at $\lambda$=1mm while the intensity distributions at 0.3mm and 9mm each only show one large peak and only a subtle secondary component.

Finally the center-to-limb variation at $\lambda$=1mm is displayed in **Fig.4**. Obviously, the predicted chromospheric internetwork pattern should be observable at most of the solar disk.

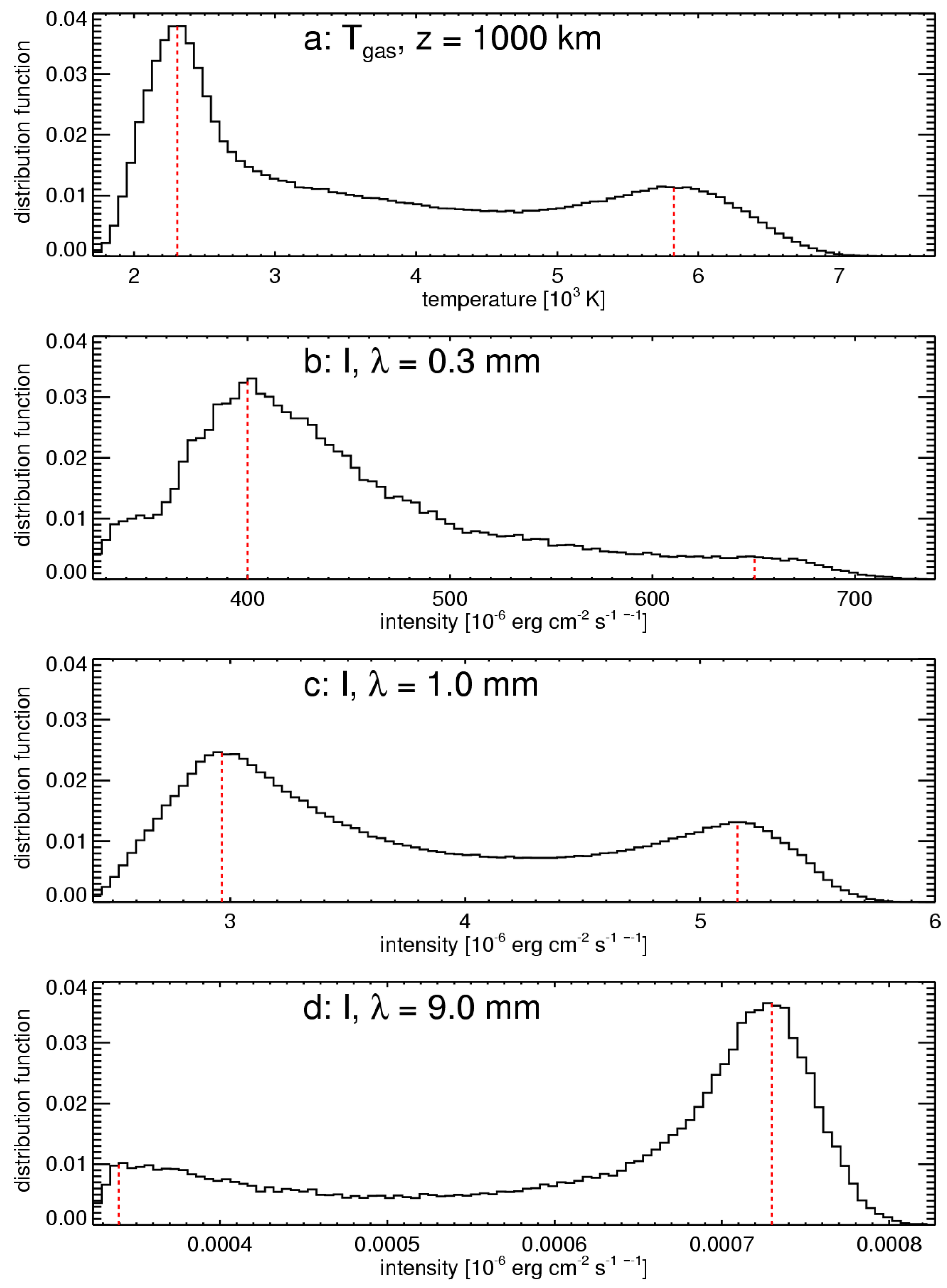


**Fig.3:** Distribution functions for temperature at z=1000 km **(a)** and emergent intensity at $\lambda$= 0.3 mm, 1.0 mm, and 9.0 mm **(b-d)**. The dotted lines separate photosphere and chromosphere at z=500km. The red dashed lines mark the height of the maximum contribution.

## Conclusions

A comparison with future ALMA observations will provide an ultimate test for present and future models of the solar atmosphere. In particular the intensity at a wavelength of $\lambda$=1mm maps closely the thermal structure and might thus be of great value for understanding the hithereto hotly debated structure and dynamics of the solar chromosphere (see also Loukitcheva et al. 2004). Due to the almost direct translation of temperature into intensity and the high time resolution of the ALMA instrument, also the results concerning the dynamics of the (model) chromosphere will be easily comparable with future observations.

## References


***Bastian, 2002, Astron.Nachr., 323, 271***
***Freytag, Steffen, Dorch, 2002, Astron.Nachr., 323, 213***
***Loukitcheva, Solanki, Carlsson, Stein, 2004, A&A 419, 747***
***Wedemeyer, Freytag, Steffen, Ludwig, Holweger, 2004, A&A 414, 1121***


*Note: There will also be a talk in the splinter meeting „Imaging of Cool Stars“ (Thu. afternoon), incl. animations.*

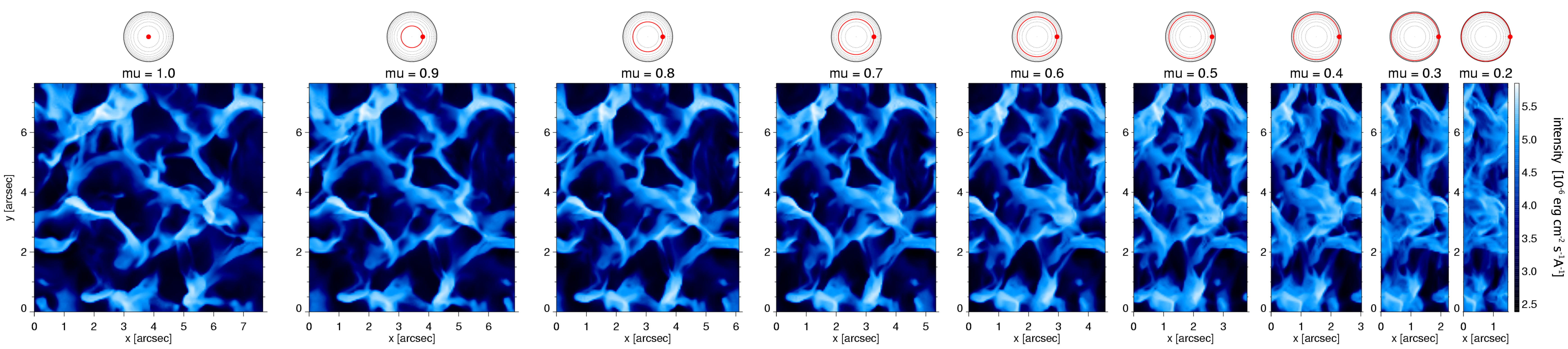


**Fig.4:** Emergent intensity at $\lambda$= 1.0 mm for different inclination angles $\mu$=cos $\theta$, ranging from 1.0 (disk center) to 0.2 (close to limb). The sketches above each panel show the corresponding position on the solar disk.